GENIUS AND THE GENIUS TF: A NEW OBSERVATORY FOR WIMP DARK MATTER AND NEUTRINOLESS DOUBLE BETA DECAY

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The GENIUS proposal is described and some of it's physics potential is outlined. Also in the light of the contradictive results from the DAMA and CDMS experiments the Genius TF, a new experimental setup is proposed. The Genius TF could probe the DAMA evidence region using the WIMP nucleus recoil signal and WIMP annual modulation signature simultaneously. Besides that it can prove the long term feasibility of the detector technique to be implemented into the GENIUS setup and will in this sense be a first step towards the realization of the GENIUS experiment.

1 Introduction

The topic of Dark Matter search has lately gained particular actuality by the results of the DAMA [1] and CDMS [2] experiments. The DAMA collaboration claims to see positive evidence for WIMP dark matter using the annual modulation signature, whereas the CDMS experiment seems to almost exclude fully the DAMA allowed cross-sections for WIMP dark matter. It is, therefore, of utmost importance to independently test these results using both experimental approaches: to look for the WIMP-nucleus recoil signal and for the annual modulation effect. However, should the positive DAMA WIMP evidence be disproven, a large step forward in terms of increasing the sensitivity of Dark Matter experiments is needed in order to obtain relevant data concerning WIMP dark matter. In this article we shortly highlight the physics potential of the GENIUS project [3,4,5] regarding WIMP Dark Matter search, neutrinoless double beta decay and the real time observation of Solar neutrinos and we introduce the Genius TF [6,7,8], a new experimental setup to probe the evidence region favoured by the DAMA experiment [1] and to test the prerequisites neccessary to realize the Genius project.

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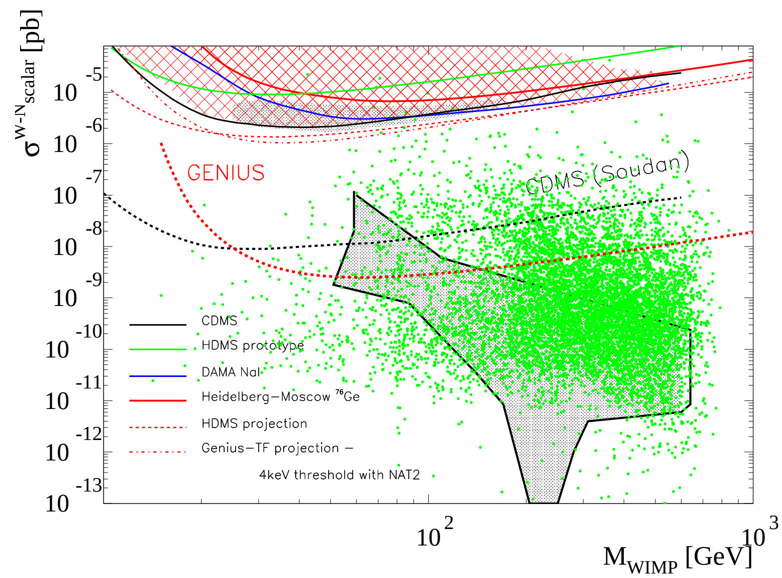

Figure 1. Exclusion plot of the scalar WIMP-nucleon elastic scattering cross section as a function of the WIMP mass. Plotted are excluded areas from the presently most sensitive direct detection experiments (hatched area DAMA [11], CDMS [2], Heidelberg-Moscow [12], HDMS prototype [13]) and some projections for experiments running or being presently under construction (HDMS, Genius TF [6,7]). The small shaded area represents the 2σ evidence region from the DAMA experiment [1]. The extrapolated sensitivities of future experiments (GENIUS [5], CDMS at Soudan [2]) are also shown. The scatter plot corresponds to predictions from theoretical considerations in the MSSM with relaxed unification conditions [14]. The large shaded area corresponds to calculations in the mSUGRA-inspired framework of the MSSM, with universality relations for the parameters at GUT scale [15].

2 The GENIUS experiment

In order to achieve a dramatic step forward regarding background reduction, a new experimental technique is needed. The GENIUS project uses the concept of application of standard detection techniques while removing all dangerous contaminations from the direct vicinity of the detectors.

2.1 The concept of the GENIUS experiment

The GENIUS project [3,4,5] is based on the idea to operate 'naked' HPGe crystals directly in liquid nitrogen [9]. The naked Germanium crystals are

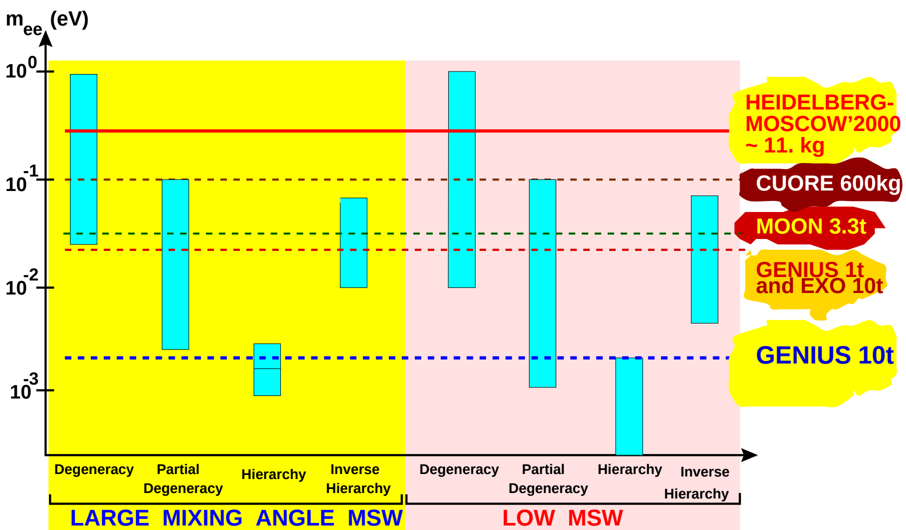

Figure 2. Summary of values for $\langle m_\nu \rangle$ (here denoted as m_{ee}) expected from present results of neutrino oscillation experiments in the different neutrino mass scenario schemes (from [16]). The expectations are compared with the recent neutrino mass limits *obtained* from the Heidelberg–Moscow [20] experiment as well as the expected sensitivities for the CUORE [21], MOON [22] proposals and the 1 ton and 10 ton proposal of GENIUS [3,5]

located in a huge nitrogen tank (diameter 12-13 m). This way all dangerous contaminations from the direct vicinity of the crystals are removed. This has the great advantage that the liquid nitrogen which is very clean with respect to radiopurity due to its production process (fractional distillation), can act simultaneously as cooling medium and shield against external activities. The conceptual design of the experiment is shown in figure 3.

It has been shown that with this approach a reduction of background by three to four orders of magnitude can be achieved [3,4,5,7,8]. The final reachable background index with a 12 m diameter GENIUS tank is estimated to be around $\sim 10^{-2}$ counts/(kg keV y) in the low-energy region below 50 keV. The sensitivity regarding WIMP Dark Matter search reachable with this background and a total detector mass of 100 kg of natural Germanium can be seen in Fig. 1.

With a background of $\sim$ 0.1 counts/(t keV y), which can be reached with this device in the energy region around the Q-value of the neutrinoless double beta decay of ^{76}Ge at 2038.5 keV, and with 1 tonne of enriched ^{76}Ge,

GENIUS would be sensitive to an effective Majorana neutrino mass down to ~0.01 eV. This will allow already to test many different neutrino mass scenarios (see figure 2). If the sensitivity of GENIUS would be increased to a level of $\langle m_\nu \rangle \sim 0.001$ eV (using 10 tonnes of ^{76}Ge), this would allow to test *all* neutrino mass scenarios allowed by present neutrino oscillation experiments - except for one, the (not favoured) hierarchical LOW solution. For a detailed discussion see [16,17,18,19].

With a background index of 10^{-3}counts/(kg keV y) in the energy region below 200 keV, which can be reached with a tank size of 13 m diameter and some improved shielding[23,24], GENIUS (10 tons) would be able to see the full solar pp neutrino spectrum in real time [23,5,24], with a count rate being a factor of 30-60 larger than a 20 tonnes LENS detector, and with a threshold of 11 keV or 19 keV.

2.2 Tritium production in HPGe at sea level

As evident from previous considerations of the expected background [5,10], great care has to be taken about the cosmogenic isotopes produced inside the HPGe crystals at sea level. However, with an additional shield against the hard component of cosmic rays during fabrication, the good sensitivity for dark matter can be maintained.

Especially the production of ^{68}Ge from the isotope ^{70}Ge can affect the sensitivity due to the 10.37 keV X-ray emitted by the decay of ^{68}Ge to ^{68}Ga. In the main reaction leading to ^{68}Ge enhancement tritium is produced through the process ^{70}Ge(n,t)^{68}Ge. Tritium has a half life of 12.35 years and can thus not be deactivated within a reasonable time. ^{3}H is a β emitter with a Q-value of 18.6 keV.

The cosmogenic production rate of ^{3}H in natural germanium has been estimated through simulations in [25,26] using the cosmic neutron fluxes cited in [27,28]. For natural germanium it is estimated to be less than $\sim$ 200 atoms per day and kg material. Using this upper limit for tritium production at sea level with an overall fabrication time of ten days this would mean a tritium abundance of $\sim$ 2000 atoms per kilogram material. With the half life of 12.3 years this results in a decay rate of ~3.6 μBq/kg equivalent to ~113 decays per year (this is in very good agreement with the result in [29]). Even assuming an energy threshold of 12 keV and taking into account the spectral shape of tritium decay this yields an event rate of approximately 2 counts/(kg keV y) in the energy region between 12 keV and 19 keV, which is by two orders of magnitude above the allowed count rate required for GENIUS as a dark matter detector.

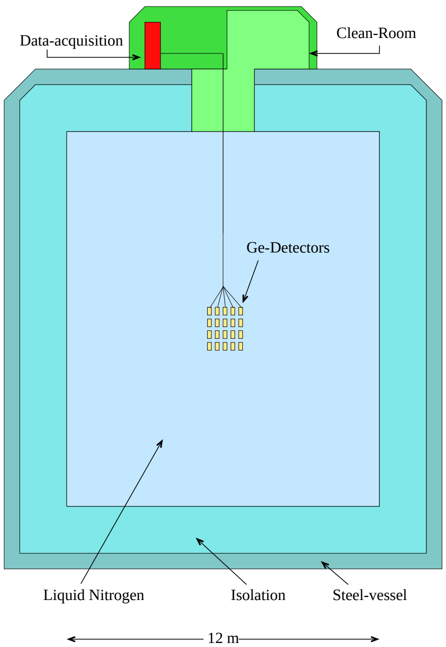

Figure 3. Schematic view of the GENIUS project. An array of 100 kg of natural HPGe detectors for the WIMP dark matter search (first step) or 1 to 10 t of enriched ^{76}Ge for the double beta decay search (final setup) is hanging on a support structure in the middle of the tank immersed in liquid nitrogen. The size of the nitrogen shield would be 12 meters in diameter at least. On top of the tank a special low level clean room and the room for the electronics and data acquisition will be placed.

This consideration drastically shows the importance of proper planning of the crystal production and transportation. To avoid major problems with cosmogenic isotopes it is therefore essential to minimize the exposure of the crystals to cosmic rays at sea level.

It is therefore planned to shield the detector material during the complete 78 hours of production after the zone refining and approximately one week of transportation periods using concrete with a thickness equivalent to $\sim$ 5 mwe. Heavy concrete can be produced with a density up to 5.9 g/cm^3. Thus an additional heavy concrete layer of 1 m could act as a shield of roughly 5 mwe. This reduces the hard nucleonic component mainly responsible for the cosmogenic isotope production by up to two orders of magnitude [9]. A further increase of shielding strength does not seem to be reasonable since the

cosmogenic production through fast muons which is by approximately two orders of magnitude less than through the hadronic component can not be shielded whatsoever.

With such a protection a reduction of the tritium production by a factor of ~ 30 (see figures 2 and 3 in [9]) can be obtained. In this way the final background from tritium in the energy interval between 12 keV and 19 keV would be $\sim 1.6 \times 10^{-2}$ counts/(kg keV y) without additional transportation and $\sim 5.6 \times 10^{-2}$ counts/(kg keV y) with a week of transport from the fabrication site to the site of the experiment.

3 The Genius-TF

It has been shown[30,8] that with a setup using a conventional shield, a sensitivity can be reached which allows for a test of the DAMA evidence region within a short time period. With an active mass of the detector of approximately 40 kg, projected for the Genius-TF (see Fig. 4), in which the background index will be maintained, not only the WIMP-nucleon recoil spectrum, but also the expected signature of WIMP dark matter in form of the annual modulation signal could be tested within a reasonable time window with a sensitivity probing the full DAMA evidence region [6,7,31].

The Genius Test Facility could test the following points: the long term stability of 'naked' HPGe-detectors in liquid nitrogen, the possibility of constructing a feasible holder system and in addition the DAMA evidence contour, through testing the expected signal and signature. The GENIUS-TF will also be a suitable place to develop and test the electronics needed for the GENIUS experiment. The data acquisition system should be based on a modular structure being capable of taking data from up to 300 detectors simultaneously.

3.1 The Test Facility

The concept of the GENIUS proposal has the great advantage that no individual cryostat system is needed. Instead the HPGe crystals are surrounded by liquid nitrogen of much higher radiopurity which in addition provides ideal cooling and shielding against external radiation. This opens the new research potentials for the Genius project [3,4].

It is proposed to install a setup with up to fourteen detectors on a small scale in order to be sensitive in the range of the DAMA result [1] on a short time scale and to prove the long term stability of the new detector concept.

The design is shown in figure 4. It is based on a dewar made from low-

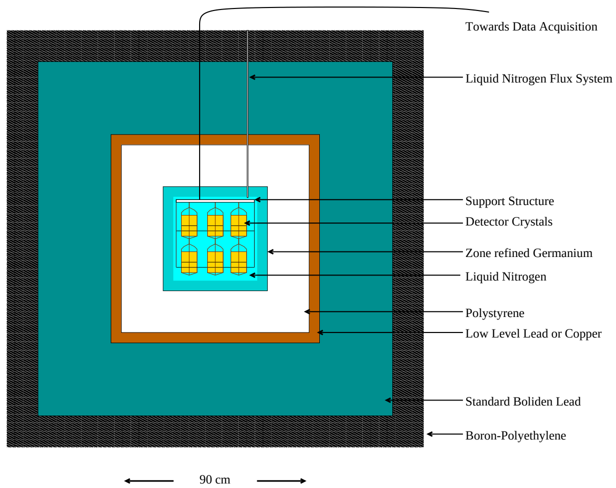

Figure 4. Conceptual design of the Genius TF. Up to 14 detectors will be housed in the inner detector chamber, filled with liquid nitrogen. As a first shield 5 cm of zone refined Germanium will be used. Behind the 20 cm of polystyrene isolation another 35 cm of low level lead and a 15 cm borated polyethylene shield will complete the setup.

activity polystyrene and on a shield of zone refined germanium bricks inside the dewar and low activity lead outside the dewar. A layer of boron loaded polyethylene plates for suppression of neutron-induced background completes the shield.

340 kg of zone-refined high-purity Germanium bricks will serve as the inner layer to shield the 'naked' HPGe detector against the less radio-pure polystyrene. Also the first 5cm layer outside the polystyrene-dewar needs to be of extreme radiopurity. The same type of copper as installed in the Heidelberg-Moscow experiment, and/or some complementary low-level lead could be used. To shield the external γ rays (natural radioactivity from the surroundings) an overall lead layer of approximately 35 cm is needed.

Using this concept an inner detector chamber of 40 cm$\times$40 cm$\times$40 cm would be sufficient to house up to seven HPGe-detectors in one layer or 14 detectors in two layers. This will allow for the development and test of a holder system for the same amount of crystals.

The overall dimension of the experiment will be 1.8 m$\times$1.8 m$\times$1.8 m thus fitting in one of the buildings of the Heidelberg-Moscow experiment which is used momentarily for material measurements.

The background considerations and simulations discussed in [7], which extend those of [30] suggest that a reduction of the background by a factor of ∼5-10 with respect to the Heidelberg-Moscow-Experiment can be attained with the proposed setup.

Assuming a final target mass of 40 kg, an energy threshold of 12 keV and a background index of 4 counts/(kg keV y) corresponding to ~ 0.01 counts/(kg keV d) in the energy region between 12 keV and 100 keV the Genius TF would need a significance of 190 kg y to see the claimed DAMA annual modulation with 95% probability and 90%C.L. (see [32]). This corresponds to an overall measuring time of approximately five years which would correspond to the life time of this experiment.

However, the new detectors will have an energy threshold of 0.5 keV (four detectors with 2.5 kg weight each, and this threshold have been produced already) thus allowing for the use of the experimental spectrum in the energy range between the threshold and the X-ray peaks seen from the cosmogenically produced isotopes. This will significantly improve the sensitivity of the Genius TF on the annual modulation effect.

In the energy region around the Q-value of the double beta decay of ^{76}Ge at 2038.5 keV a background index of $\sim 7 \times 10^{-3}$counts/(kg keV y) could be reached, leading to a sensitivity for the effective Majorana neutrino mass down to 0.15 eV with 90% C.L. [6,7]

The construction of the setup will be started in 2001. First results may be expected in the end of the year 2002.

4 Conclusions

The large physics potential of the GENIUS project regarding WIMP Dark Matter search, neutrinoless double beta decay search and real time observation of solar pp-neutrinos has been briefly outlined. We presented the Genius TF, a test facility for the GENIUS project, whose construction started in early 2001. The Genius TF can, according to Monte Carlo simulations, reach a background of $\sim$ 2-4 counts/(kg keV y) in the energy region between 11 keV and 100 keV. Thus it could for the first time probe the DAMA evidence region using both, the WIMP-nuclear recoil signal and the annual modulation signature.

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